analysis purposes, naval spent nuclear fuel is conservatively modeled as commercial spent nuclear fuel (DIRS 152059-BSC 2001, all; DIRS 153849-DOE 2001, Section 4.2.6.3.9, p. 4-257).

5.1.2 INVENTORY OF CHEMICALLY TOXIC MATERIAL

DOE is not proposing to dispose of chemically toxic waste in the potential repository. However, the degradation of engineered materials that would be used in repository construction and engineered barrier systems would result in corrosion products that contain chemically toxic materials.

A screening analysis reported in Appendix I (Section I.6.1) showed that the only chemical materials of concern for the 10,000-year analysis period were those released as the external wall of the waste package and the waste package support pallet materials corroded. The chemicals of concern would be chromium, nickel, molybdenum, and vanadium. The exposed surface areas that would corrode include Alloy-22 surfaces (drip shield rails, outer layer of waste packages, and portions of the emplacement pallets) and stainless steel 316NG surfaces (portions of the emplacement pallets).

The total quantities of materials would be 86,000,000 kilograms (190,000,000 pounds) of Alloy-22 (DIRS 150558-CRWMS M&O 2000, p. 6-6) containing 22.5 percent chromium, 14.5 percent molybdenum, 57.2 percent nickel, 0.35 percent vanadium (DIRS 104328-ASTM 1998, all) and 140,000,000 kilograms (310,000,000 pounds) of stainless steel, (DIRS 150558-CRWMS M&O 2000, p. 6-6) which is 17 percent chromium, 12 percent nickel and 2.5 percent molybdenum. A large percentage of the stainless steel would be inside the waste package (as an inner sleeve) and, therefore, much of this material would not be exposed until the Alloy-22 had corroded away.

5.2 System Overview

Radioactive materials in the repository would be placed at least 200 meters (660 feet) beneath the surface (DIRS 154554-BSC 2001, pp. 28-29). In physical form, the emplaced materials would be almost entirely in the form of solids with a very small fraction of the total radioactive inventory in the form of trapped gases (see Section 5.5). With the exception of a small amount of radioactive gas in the fuel rods, the primary means for the radioactive and chemically toxic materials to contact the *biosphere* would be along groundwater pathways. The materials could pose a threat to humans if the following sequence of events occurred:

- The waste packages and their contents were exposed to water
- Radionuclides or chemically toxic materials in the package materials or wastes became dissolved or mobilized in the water
- The radionuclides or chemically toxic materials were transported in water to an aquifer, and the water carrying radionuclides or chemically toxic materials was withdrawn from the aquifer through a well or at a surface-water discharge point and used directly by humans for drinking or in the human food chain (such as through irrigation or watering livestock).

Thus, the access to, and flow of, contaminated water are the most important considerations in determining potential health hazards.

5.2.1 COMPONENTS OF THE NATURAL SYSTEM

Figure 5-2 is a simplified schematic of a repository at Yucca Mountain. It shows the principal features of the natural system that could affect the long-term performance of the repository. Yucca Mountain is in a semiarid desert environment where the current average annual precipitation over the unsaturated zone flow and transport model area is 170 millimeters (7 inches), varying by specific location (DIRS 153849-DOE 2001, p. 4-38). The water table is an average of about 600 meters (2,000 feet) below the surface of the mountain. The proposed repository would be in unsaturated rock approximately midway between the desert environment and the water table.

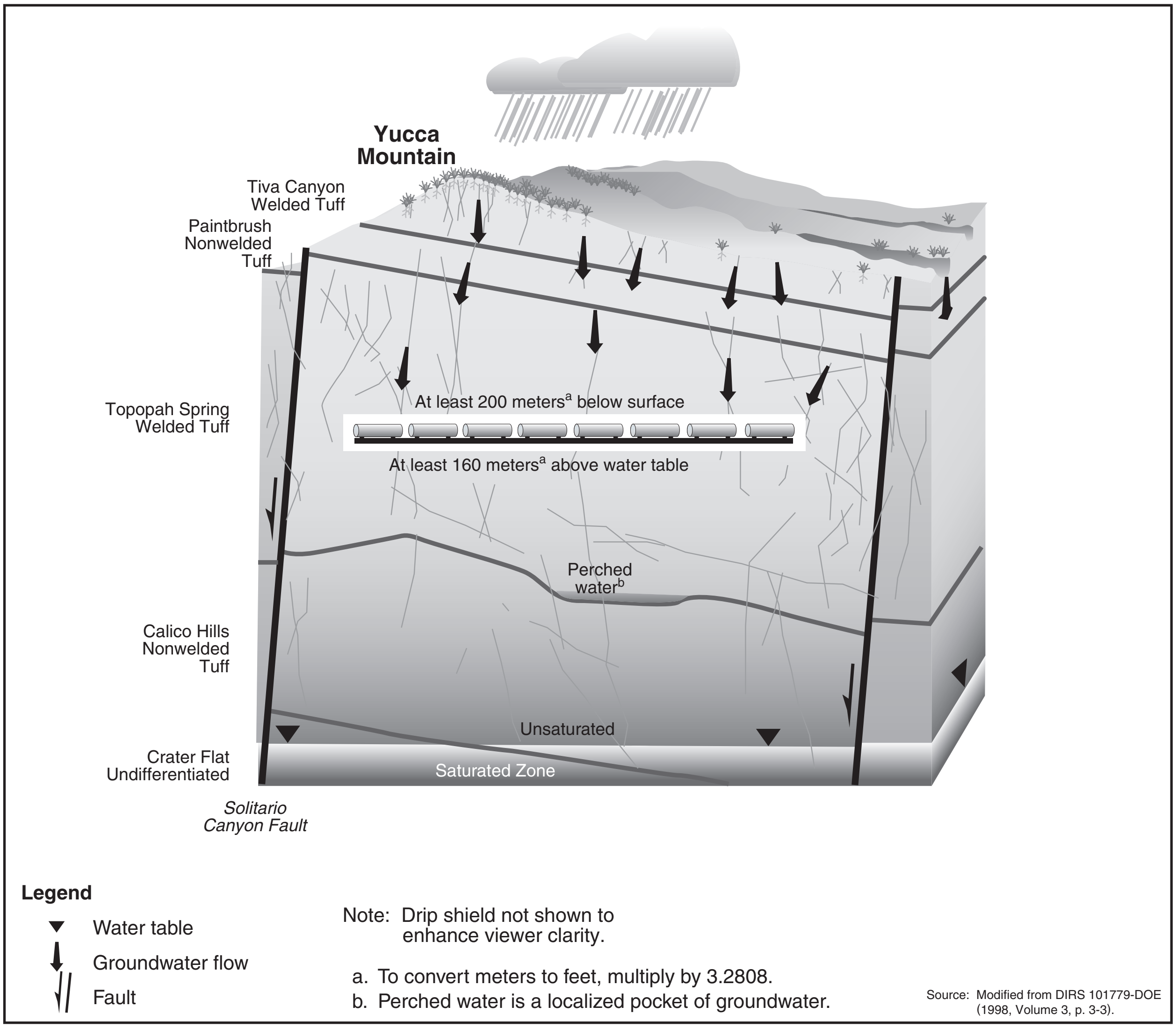

Figure 5-2. Components of the natural system.

The water table is the boundary between the unsaturated zone above and the saturated zone below. In the subsurface region above the water table, the rock contains water but the water does not fill all the open spaces in the rock. Because the open spaces are only partially filled, this region is called the unsaturated zone. Water in the unsaturated zone tends to move generally downward in response to capillary action and gravity. In contrast, water fills all the open spaces in the rock below the water table, so this region is called the saturated zone. Water in the saturated zone tends to flow laterally from higher to lower pressures. Both zones contain several different rock types, as shown in Figure 5-2. The layers of major rock types in the unsaturated zone at the Yucca Mountain site are the Tiva Canyon welded, Paintbrush nonwelded, Topopah Spring welded, Calico Hills nonwelded, and Crater Flat undifferentiated tuffs. Figure 5-2 shows two of the faults at the proposed site-the Ghost Dance fault that occurs within the repository block and the Solitario Canyon Fault that forms the western boundary of the repository block. Faults are slip zones where rock units have become displaced either vertically, laterally, or diagonally, resulting in the rock layers being discontinuous. These slip zones tend to form a thin plane in which there is more open space that acts as a channel for water. Some faults tend to fill with broken rock formed as they slip, so they take on a very different flow property from that of the surrounding rock. The proposed repository would be in the Topopah Spring welded tuff in the unsaturated zone, at least 200 meters (660 feet) below the surface and at least 160 meters (530 feet) above the water table (DIRS 154554-BSC 2001, pp. 28-29).

HYDROGEOLOGIC TERMS

Saturated zone: The area below the water table where all spaces (fractures and rock pores) are completely filled with water.

Unsaturated zone: The area between the surface and the water table where only some of the spaces (fractures and rock pores) are filled with water.

Matrix: The solid, but porous, portion of the rock.

When it rains in the Yucca Mountain vicinity, most of the water runs off and a very limited amount infiltrates the rock on the surface of the mountain. Some of the water that remains on the surface or infiltrates the rock evaporates back into the atmosphere (directly or through plant uptake and evapotranspiration). The very small amount of water that infiltrates the rock and does not evaporate percolates down through the mountain to the saturated zone (DIRS 155950-BSC 2001, Section 3.3.2.1, p. 3-17). Water that flowed through the unsaturated zone into the proposed repository could dissolve some of the waste material, if there was a breach in the package containment, and could carry it through the groundwater system to the accessible environment, where exposure to humans could occur.

5.2.2 COMPONENTS OF THE WASTE PACKAGE AND DRIP SHIELD

The waste package would consist of two concentric cylindrical containers sealed with welded lids in which DOE would place the waste forms. The inner cylinder would be stainless steel (316NG). The outer cylinder would be a corrosion-resistant nickel-based alloy (Alloy-22). Alloy-22 would protect the underlying structural material (stainless steel) from corrosion, while the structural material would support the thinner, corrosion-resistant material. The current design calls for emplacement of a titanium drip shield over the waste packages just prior to repository closure. With the drip shield in place, the Alloy-22 outer cylinder would be the second corrosion barrier protecting the waste from contact with water. The use of two distinctly different corrosion-resistant materials would reduce the probability that a single environmental condition could cause the failure of both materials. Before the double-walled waste package was sealed, helium would be added as a fill gas. The helium would prevent corrosion of the waste form and help transfer heat from the waste form itself to the inner wall of the waste package. Moving heat away from the waste form would be one important means of controlling waste form temperatures. This would help preserve the integrity of the metal cladding on the fuel rods, thus extending the life of an already-existing barrier that protects the waste from water.

5.2.3 VISUALIZATION OF THE REPOSITORY SYSTEM FOR ANALYSIS OF LONG-TERM PERFORMANCE

In general, the repository system was modeled as a series of processes linked together, one after the other, spatially from top to bottom in the mountain. From a computer-modeling standpoint, it is important to break the system into smaller portions that relate to the way information is collected. In reality, an operating repository system would be completely interconnected, and virtually no process would be independent of other processes. However, the complexity of such a system demands some idealization of the system for an analysis to be performed.

The first step in the visualization of the system is the development of a listing of all the possible features, events, and processes that could apply to the behavior of the system. An example of a *feature* is the existence of a fault, an example of an *event* is a seismic event (earthquake), and an example of a *process* is the gradual degradation of the waste package wall by general corrosion. The list is then screened using various types of analyses to determine what features, events, and processes should be included in the modeling. The chosen features, events, and processes are then assembled into scenarios, which are descriptions of how features, events, and processes link together to result in a certain outcome (see Appendix I, Section I.2.1, for further detail).

The elements of the TSPA model are organized into the following categories, which are generally related to various parts of the system:

- Unsaturated zone flow
- Engineered barrier system environments
- Waste package and drip shield degradation
- Waste form degradation
- Engineered barrier transport
- Unsaturated zone transport
- Saturated zone flow and transport
- Biosphere

The individual models associated with these elements are discussed in Appendix I, Sections I.2.2 through I.2.9.

In addition, the following special scenarios are also discussed in Appendix I, Sections I.2.10 through I.2.13:

- Volcanism
- Human intrusion
- Nuclear criticality
- Atmospheric radiological transport

During the development of the TSPA model, DOE often had to make assumptions. The main reason for assumptions was to account for situations where there was limited data. With additional data, it may be possible to present a more “realistic” representation, usually as a statistical distribution. If data are limited, it is necessary to make assumptions and use associated conservative data values. The Nuclear Regulatory Commission and Environmental Protection Agency rulemaking processes acknowledged that uncertainty about physical processes acting over the large space and time scales of interest will remain, even after many years of site characterization. The long-term analysis does not seek an exact prediction but rather seeks to establish a representative projection. The list of assumptions is too large to include here. Table 5-3 is an index to a series of tables that describe in detail the assumptions in the model and associated key attributes. The detailed information is in the Total System Performance Assessment-Site Recommendation document (DIRS 153246-CRWMS M&O 2000, pp. F-2 to F-9).

Table 5-3. Cross-reference to key assumptions and associated attributes in the TSPA model.[a]

Category	TSPA-Site Recommendation table[b]
Unsaturated zone flow and transport	F-1
Near-field environment	F-2
Engineered barrier system—chemical environment and radionuclide transport	F-3
Drip shield/waste package	F-4
Inventory component	F-5
In-package chemistry component	F-6
Commercial spent nuclear fuel degradation component	F-7
Defense spent nuclear fuel degradation component	F-8
High-level radioactive waste degradation component	F-9
Dissolved concentration component	F-10
Colloidal concentration component	F-11
Saturated zone flow and transport	F-12
Biosphere	F-13
Disruptive events	F-14

a. Some assumptions were modified in the *Supplemental Science and Performance Analyses* (DIRS 155950-BSC 2001, all). See Table 1-1 of that document for a summary of areas where assumptions were modified or revised.
b. See DIRS 153246-CRWMS M&O (2000, pp. F-2 to F-9).

5.2.4 UNCERTAINTY

As with any impact estimate, there is a level of uncertainty associated with the forecast, especially when estimating impacts over thousands of years. Uncertainty can be defined as the measure of confidence in the forecast related to determining how a system will operate or respond. The amount of uncertainty associated with an impact estimate is a reflection of several factors, including the following four factors:

- An understanding of the components of a system (such as human and societal, hydrogeologic, or engineered) and how those components interact. The greater the number of components, the more complex the system, the lesser the capability to measure or understand how the system or components produce a greater potential for uncertainty. Similarly, fewer studies or more assumptions produce greater potential for uncertainty.

- The time scale over which estimates are made. Longer time scales for forecasts produce greater potential for uncertainty.

- The available computation and modeling tools. More general computation tools or more assumptions produce greater potential for uncertainty.

- The stability and uniformity (or variability) of the components and system being evaluated. Less stability and uniformity (that is, greater variability) produces a greater potential for uncertainty.

DOE recognizes that uncertainties exist from the onset of an analysis; however, forecasts are valuable in the decisionmaking process because they provide insight based on the best information and scientific judgments available. The following section discusses uncertainties in the context of possible effects on the impact estimates reported in this chapter. The discussion is divided to address:

- Uncertainty associated with societal changes and climate
- Uncertainty associated with currently unavailable data
- Uncertainty associated with models and model parameters

5.2.4.1 Uncertainty Associated with Societal Changes, Climate, and Other Long-Term Phenomena

General guidance on predicting the evolution of society has been provided by the National Academy of Sciences. In its report, *Technical Bases for Yucca Mountain Standards* (DIRS 100018-National Research Council 1995, all), the Committee on Technical Bases for Yucca Mountain Standards concluded that there is no scientific basis for predicting future human behavior. The study recommends policy decisions that specify the use of default (or reference) scenarios to incorporate future human behaviors in compliance assessment calculations. The analysis in this chapter generally follows the recommended approach, using as defaults societal conditions as they exist today and the assumption that populations would remain at their present locations. These assumptions, while appropriate for estimating impacts for comparison with other proposed actions, are not realistic because it is likely that populations will move and change in size. Therefore, DOE has chosen to project population size for 2035 (see Chapter 3, Section 3.1.7.1). If populations were to move closer to or increase in size in the Yucca Mountain groundwater region of influence, the radiation dose and resultant impacts could increase. DOE does not have the means to predict such changes quantitatively with great accuracy; therefore, the analysis does not attempt to quantify the resultant effects on overall impacts. In addition, the analysis does not address the potential benefits from future human activities including improved technology for removing radioactive materials from drinking water or the environment or medical advances such as cures for cancer.

Estimates of future climatic conditions are based on what is known about the past, with consideration given to climate impacts caused by human activities. Calcite in Devils Hole, a fissure in the ground approximately 40 kilometers (25 miles) southeast of Yucca Mountain, provides the best-dated record of climate changes over the past 500,000 years. The record shows continual variation, often with very rapid jumps, between cold glacial climates (for the Great Basin, these are called pluvial periods) and warm interglacial climates similar to the present. Fluctuations average 100,000 years in length (DIRS 153038-CRWMS M&O 2000, Section 6.4.1). The past climate cycles were idealized into a regular cycle of pulses, which were repeated throughout the period of the forecast. This method inherently assumes that the future will repeat the past. However, while current understanding of the causes of climate change allows some confidence in this approach, a considerable amount of conservatism was built into the models to account for possible climate uncertainties. For example, a large range of water fluxes was used to reflect the wide rainfall variations that could occur over thousands and hundreds of thousands of years (DIRS 155950-BSC 2001, Section 3.3.2.6). The analysis assumed that the current climate is the driest it will ever be at Yucca Mountain.

5.2.4.2 Uncertainty Associated with Currently Unavailable Data

Some uncertainties for input parameters or models result from gaps in available data. Such gaps may be due to the status of research (with further data expected later) or conditions that limit gathering of data (such as the need to conduct tests over impractical long periods of time or the necessity to not overly disturb the emplacement site). Uncertainty associated with currently unavailable data is a subset of parameter and model uncertainty that is discussed further in Section 5.2.4.3.

As further discussed in Section 5.2.4.3, the use of parameter distributions and studies of alternative models can provide understanding of how the lack of data affects the range of the impact results. Furthermore, sensitivity studies (see Section 5.2.4.3.4) can also provide insight into the importance of particular parameters. The sensitivity studies sometimes identify data with a small contribution to the results, thereby mitigating concerns arising from their unavailability.

The fact that some data are currently unavailable does not necessarily preclude providing adequate assessment of long-term impacts. When the Draft EIS and the Supplement to the Draft EIS were prepared there was sufficient information to provide an adequate analysis of the long-term performance impacts.

However, additional data have been generated since the publication of those documents. These data have helped improve characterization of the range of impacts in this Final EIS over those reported in the Draft EIS. Some examples of the additional data and their uses are the following:

- Concentrations of chemical components in the rock such as chloride, bromide, and sulfate are being measured, and the results will aid in identifying fast paths for water flow. Ongoing analyses of the isotopic ages of fracture-lining minerals provide preferential information on the history of water movement. These studies show how and when water has moved through the unsaturated zone and reveal characteristics of the water, such as the chemical composition and temperature. This information has been factored into modeling of the unsaturated zone (DIRS 155950-BSC 2001, Section 3.3.2)

- The effects of heating on water seepage into emplacement drifts were investigated in a drift-scale thermal test and by laboratory experiments that support models for predicting the effects of coupled processes over much longer periods (DIRS 155950-BSC 2001, Section 3.3.3)

- Accelerated corrosion testing of Alloy-22 has allowed more definitive quantification of corrosion rates used in improvements in the waste package degradation model (DIRS 155950-BSC 2001, Section 7.2.2)

5.2.4.3 Uncertainty Associated with Models and Model Parameters

The long-term performance model used to assess the impacts from groundwater migration includes a large number of submodels and requires a large amount of input data. The model must account for important features of the system, likely events, and processes that would contribute to the release and migration of materials. Because of the long periods being simulated, the complexity and variability of a natural system, and several other factors, the performance modeling must deal with a large degree of uncertainty. This section discusses the nature of the uncertainties and how they were accounted for in this EIS and their implication to interpretation of impact results. The *Supplemental Science and Performance Analysis* (DIRS 155950-BSC 2001, all) contains further details concerning this subject.

5.2.4.3.1 *Variability Versus Uncertainty*

A variable feature, event, or process is one that changes over space or with time. Examples include the porosity of the rock mass, the temperature in the repository, and the geochemical environment in the repository drifts. If all information was available, such parameters would be best expressed as known mathematical functions of space and time. In contrast, uncertainty relates to a lack of knowledge regarding a feature, event, or process-one whose properties or future outcome cannot be predicted. Four types of uncertainty are typically considered: value uncertainty, *conceptual model* uncertainty, numerical model uncertainty, and uncertainty regarding future events. The treatment of a feature, event, or process as purely variable or purely uncertain can lead to different modeling results.

Uncertainty and variability are sometimes related. The exact nature of the variability in a natural system cannot be known because all parts of the system cannot be observed. For example, DOE cannot dig up all the rock in Yucca Mountain and determine that the positioning of the rock layers is exactly as suggested by core sample data. Therefore, there is uncertainty about the properties of the rock at specific locations in the mountain because properties change with distance and it is not known how much they change at any given location. If the variability can be appropriately quantified or measured, a model usually can be developed to include this variability. If the variability cannot be physically quantified or estimated, it should be treated as uncertainty (lack of knowledge). However, the ability to model some types of spatial variability can be limited not only by lack of data but also by the capacity of a computer to complete calculations (for example, if one simulation took weeks or months to complete). In these instances, variability must be simplified in such a way as to be conservative (that is, the simulation would overestimate the impact).

Two basic tools were used in the analysis to deal with uncertainty and variability: alternative conceptual models and probability theory. Alternative conceptual models were used to handle uncertainty in the understanding of a key physical-chemical process controlling system behavior. Probability theory was used to understand the impacts of uncertainty in specific model parameters (that is, would results change if the parameter value was different). In particular, uncertain processes often required different conceptual models. For example, different conceptual models of how water in fractures communicates with water in the smaller pores or the matrix of the rock in the unsaturated zone lead to different flow and transport models. Sometimes conceptual models are not mutually exclusive (for example, both matrix and fracture flow might occur), and sometimes they do not exhaustively cover all possibilities (apparently matrix and fracture flow do cover all possibilities). These examples indicate that the use of alternative conceptual models, while often necessary to characterize some types of uncertainty, is not always as exact as desired.

A process of weighting alternative conceptual models (as described below) was used in the long-term consequence analysis to account for uncertainties in conceptual models. The Monte Carlo sampling technique was used for handling uncertainty in specific model parameters and for alternative conceptual models that were weighted beforehand with specific probabilities. The method involves random sampling of ranges of likely values, or *distributions*, for all uncertain input parameters. Distributions describe the probability of a particular value in the range. A common type of distribution is the familiar "bell-shaped" curve, also known as the *normal distribution*. Parameters in the consequence analysis are described by many different types of distributions appropriate for how the values and their probabilities are understood. Numerous realizations of the repository system behavior were calculated, each based on one set of samples of all the inputs. Each total system realization had an associated probability so that there is some perspective on the likelihood of that set of circumstances occurring. The Monte Carlo method yields a range for any chosen performance measure (for example, peak annual individual dose in a given period at a given location) along with a probability for each value in the range. In other words, it gives an estimate of repository performance and determines the possible errors based on the estimate. In this chapter, the impact estimates are expressed as the mean of all the realizations and the 95th-percentile value (that is, the value for which 95 percent of the results were smaller).

CALCULATING THE MEAN AND 95TH-PERCENTILE RESULTS

DOE calculated a mean and 95th-percentile dose history by selecting the mean and 95th-percentile value at each time step in the simulation. Thus, the mean dose history consisted of the average of all 300 realizations of dose rate at each time step, and the 95th-percentile dose history consisted of the 95th-percentile at each time step. The EIS analysis determined the peak value from these dose histories, and the EIS discusses the "peak of the mean dose history" and the "peak of the 95th-percentile dose history."

5.2.4.3.2 *Weighting of Alternative Conceptual Models*

In some cases, modeling alternatives form a continuum, and sampling from the continuum of assumptions fits naturally in the Monte Carlo framework of sampling from probability distributions. In other cases, the assumptions or models are discrete choices. In particular, some processes are so highly uncertain that there are not enough data to justify developing continuous probability distributions over the postulated ranges of behavior. In such cases, a high degree of sampling is unwarranted, and an analysis often models two or three cases that are assumed to encompass the likely behavior.

There were two possible approaches to incorporating discrete alternative models in the performance analysis: weighting all models into one comprehensive Monte Carlo simulation (lumping), or keeping the discrete models separate and performing multiple Monte Carlo simulations for each discrete model (splitting). The main results in Section 5.4 were developed using the splitting approach because they were based on a limited range of uncertainty. Based on expert judgment (and to some extent the finite time and resources that could be applied to the analysis effort), the analysis used a best estimate of the more likely ranges of model behavior and parameter ranges. Some alternative models were not included in the analysis, and some parameter ranges of the included models were narrowed. Because of this narrowed range of models and parameters, the results are conditional, meaning that they depend on certain models and parameters being held constant or having their variance restricted. One such condition is the specific design of the repository and the waste packages in the design evaluated in this EIS. Another important condition is that the cladding on the spent nuclear fuel can be depended on as a barrier. Other conditional results were used to characterize the effect of certain assumptions. For example, splitting was done to consider such events as human intrusion (Section 5.7.1), igneous activity (Section 5.7.2), and criticality (Section 5.8). The consequences of these types of events are not part of results given in Section 5.4; rather they are reported as added impacts with certain probabilities of occurrence.

5.2.4.3.3 *Uncertainty and the Proposed Action*

The analysis for the Proposed Action encompassed many of the underlying uncertainties. It included some of all four types of uncertainty: value or parameter uncertainty, conceptual model uncertainty, numerical model uncertainty, and future-event uncertainty. Therefore, the results represent a "lumping" approach. Uncertainty not lumped into the modeling, which produced the central results in Section 5.4, was addressed discretely in alternative models, alternative features, and alternative events such as human intrusion. These alternatives were "split" from the nominal results, and their effects on performance are described separately.

5.2.4.3.4 *Uncertainty and Sensitivity*

In addition to accounting for the uncertainty, characteristics of the engineered and natural systems (such as the unsaturated and saturated zones of the groundwater system) that would have the most influence on repository performance also need to be understood. This information helps define uncertainty in the context of what would most influence the results. This concept is called sensitivity analysis. A number of methods are used to explain the results and quantify sensitivities. Total system performance is a function of sensitivity (if a parameter is varied, how much do the performance measures change) and uncertainty (how much variation of a parameter is reasonable). For example, the long-term performance results could be very sensitive to a certain parameter, but the value for the parameter is exactly known. In the uncertainty analysis techniques described below, that parameter would not be regarded as important. However, many parameters in the analyses do have an associated uncertainty and do become highly important to performance. On the other hand, the level of their ranking can depend on the width of the assigned uncertainty range.

Many of the important uncertain parameters were examined in alternative models. The alternative models either expand the range of the parameters beyond the expected range of uncertainty or change the weighting of the parameter distribution. For example, this type of analysis was performed for alternative models of seepage (DIRS 101779-DOE 1998, Volume 3, pp. 5-1 to 5-9) and cladding degradation (DIRS 101779-DOE 1998, Volume 3, pp. 5-32 to 5-35). An example of alternative model studies for volcanic hazards is discussed in DIRS 155950-BSC (2001, Section 14.3.1, p. 14-6).

System performance could be sensitive to repository design options, but models and parameters for these various options do not have an assigned uncertainty. Therefore, although they can be important, they do not show up as key parameters based on an uncertainty analysis. The determination of the parameters or components that are most important depends on the particular performance measure being used. This point was demonstrated in the 1993 TSPA (DIRS 100111-CRWMS M&O 1994, all; DIRS 100191-Wilson et al. 1994, all) and the Total System Performance Assessment-1995 (DIRS 100198-CRWMS M&O 1995, all). For example, these two analyses showed that the important parameters would be different for 10,000-year peak doses than for 1-million-year peak doses.

There are several techniques for analyzing uncertainties, including the use of qualitative scatter plots where the results (for example, annual individual dose) are plotted against the input parameters and visually inspected for trends. In addition, performance measures can be plotted against various subsystem outputs or surrogate performance measures (for example, waste package lifetime) to determine if that subsystem or performance surrogate would be important to performance. There are several formal mathematical techniques for analyzing the sets of realizations from a Monte Carlo analysis to extract information about the effects of parameters. Such an analysis determined the principal factors affecting the performance of the repository design.

5.2.4.3.5 *Uncertainty Analysis for the TSPA-Site Recommendation*

The Science and Engineering Report (DIRS 153849-DOE 2001, all) provides the results of a comprehensive quantitative analysis of the possible future behavior of a Yucca Mountain repository. The analysis, documented in the *Total System Performance Assessment for the Site Recommendation* (DIRS 153246-CRWMS M&O 2000, all), combined the results of detailed conceptual and numerical models of each of the individual and coupled processes in a single *probabilistic* model that can be used to assess how a repository might perform over long periods. The TSPA-Site Recommendation was a next-generation analysis after the TSPA-Viability Assessment, which DOE used for analysis of long-term performance in the Draft EIS. The Site Recommendation analysis was the result of design changes to the proposed repository and advancement in knowledge from ongoing research activities.

Despite the extensive scientific studies described in the Science and Engineering Report, DOE has always recognized that uncertainties will remain in any assessment of the performance of a repository over thousands of years, as discussed in that report (DIRS 153849-DOE 2001, Sections 1.5, 4.1, and 4.4). These uncertainties are attributable to a variety of causes, ranging from uncertainty regarding the fundamental processes that could affect radionuclide migration to uncertainty related to the design and operation of the repository. For this reason, one part of the DOE approach to dealing with uncertainty relies on multiple lines of evidence that can contribute to the understanding of the performance of the potential repository. Another part of the DOE approach is a commitment to continued testing, monitoring, and analysis beyond the possible recommendation of the site.

The TSPA-Site Recommendation model incorporated a number of uncertainties. These were uncertainties for which a realistic distribution of parameters is not identified, but rather a very conservative bounding value or bounding range was chosen. Additional studies have investigated effects of unquantified uncertainties and sensitivities in the TSPA model by better quantification of uncertainties and the affected processes. This research is documented in the Supplemental Science and Performance Analysis (DIRS 155950-BSC 2001, all). (See Appendix I, Section I.2 for more detailed discussion of the evolution of the TSPA model and application to this EIS.) A summary of areas in which the Supplemental Science and Performance Analysis model benefited from these additional uncertainty studies is provided below. The Supplemental Science and Performance Analysis (DIRS 155950-BSC 2001, all) contains full details of the studies.

Unquantified Uncertainty Analysis

Part of the work described in the Supplemental Science and Performance Analysis (DIRS 155950-BSC 2001, all) included analysis of unquantified uncertainties. Table 5-4 summarizes the elements of the model that DOE studied and indicates whether or not revised model elements were included in the Supplemental Science and Performance Analysis model. The Supplemental Science and Performance Analysis model, with additional modifications, was used for the long-term performance analysis for this

Table 5-4. Analysis of unquantified uncertainties and resulting TSPA model modifications[a] (page 1 of 2).

Process model (section of S&ER[b])	Topic of unquantified uncertainty analysis	Section of SSPA[c] Volume 1	In Supplemental TSPA[d] model
Seepage into emplacement drifts (4.2.1)	Flow- focusing in heterogeneous permeability field; episodic seepage	4.3.1, 4.3.2, 4.3.5	Yes
	Effects on rock bolts and drift degradation on seepage	4.3.3, 4.3.4	
Coupled effects on seepage (4.2.2)	Thermal effects on seepage	4.3.5	Yes
	Thermal-hydrologic-chemical effects on seepage	4.3.6	
Water diversion performance of engineered barrier system (4.2.3)	Multiscale thermal-hydrologic model, including effects of rock dryout	5.3.1	Yes
	Thermal property sets	5.3.1	Yes
	Effect of in-drift convection on temperature, humidity, invert saturations, and evaporation rates	5.3.2	
	Composition of liquid and gas entering drift	6.3.1	Yes
	Evolution of in-drift chemical environment	6.3.3	Yes
In-drift moisture distribution (4.2.5)	Environment on surface of drip shields and waste packages	5.3.2, 7.3.1	
	Condensation under drip shields	8.3.2	
	Evaporation of seepage	8.3.1, 5.3.2	Yes
	Effect of breached drip shields or waste package on seepage	8.3.3	Yes
	Waste package release flow geometry (flow- through, bathtub)	8.3.4	
Drip shield degradation and performance (4.2.4)	Local chemical environment on surface of drip shields (including magnesium, lead) and potential for initiating localized corrosion	7.3.1	
Waste package degradation and performance (4.2.4)	Local chemical environment on surface of waste packages (including magnesium, lead) and potential for initiating localized corrosion	7.3.1	
	Aging and phase stability effects on Alloy-22	7.3.2	Yes
	Uncertainty in weld stress state following mitigation	7.3.3	Yes
	Weld defects	7.3.3	Yes
	Early failure due to improper heat treatment	7.3.6	Yes
	General corrosion rate of Alloy-22: temperature dependency[e]	7.3.5	Yes
	General corrosion rate of Alloy-22: uncertainty/ variability partition	7.3.5	Yes
	Long- term stability of passive films on Alloy-22	7.3.4	
	Stress threshold for initiation of stress corrosion cracking	7.3.3	Yes
	Distribution of crack growth exponent repassivation slope	7.3.7	Yes
In-package environments (4.2.6)	Effect of HLW[f] glass degradation rate and steel degradation rate on in-package chemistry	9.3.1	Yes
Cladding degradation and performance (4.2.6)	Effect of initial perforations, creep rupture, stress corrosion cracking, localized corrosion, seismic failure, rock overburden failure, and unzipping velocity on cladding degradation	9.3.3	Yes
Defense HLW degradation and performance (4.2.6)	HLW glass degradation rates	9.3.1	
Dissolved radionuclide concentrations (4.2.6)	Solubility of neptunium, thorium, plutonium, and technetium	9.3.2	Yes
Colloid-associated radionuclide concentrations (4.2.6)	Colloid mass concentrations	9.3.4	
Engineered barrier system (invert) degradation and transport (4.2.6, 4.2.7)	Diffusion inside waste package	10.3.1	Yes
	Transport pathway from inside waste package to invert	10.3.2	
	Sorption inside waste package	10.3.4	Yes
	Sorption in invert	10.3.4	Yes
	Diffusion through invert	10.3.3	Yes
	Colloid stability in invert	10.3.5	
	Microbial transport of colloids	10.3.6	
Unsaturated zone radionuclide transport (advective pathways; retardation; dispersion; dilution) (4.2.8)	Effect of drift shadow zone-advection/diffusion splitting	11.3.1	Yes
	Effect of drift shadow zone – concentration boundary condition on engineered barrier system release rates	11.3.1	
	Effect of matrix diffusion	11.3.2, 11.3.3	
Saturated zone radionuclide flow and transport (4.2.9)	Groundwater specific discharge	12.3.1	
	Effective diffusion coefficient in volcanic tuffs	12.3.2	
	Flowing interval (fracture) porosity	12.3.2	
	Effective porosity in alluvium	12.3.2	
	Correlation of effective diffusion coefficient with matrix porosity	12.3.2	
	Bulk density of alluvium	12.3.2	Yes
	Retardation for radionuclides irreversibly sorbed on colloids in alluvium	12.3.2	
	Sorption coefficient in alluvium for iodine, technetium	12.3.2	Yes
	Sorption coefficient in alluvium for neptunium, uranium	12.3.2	
	Sorption coefficient for neptunium in volcanic tuffs	12.3.2	
	Effective longitudinal dispersivity	12.3.2	

Table 5-4. Analysis of unquantified uncertainties and resulting TSPA model modifications.[a] (page 2 of 2).

Process model (section of S&ER[b])	Topic of unquantified uncertainty analysis	Section of SSPA[c] Volume 1	In Supplemental TSPA[d] model
Biosphere (4.2.10)[g]	Individual of interest	13.3.1	
	Comparison of dose assessment methods	13.3.2	
	Radionuclide removal from soil by leaching	13.3.3	
	Uncertainties not captured by GENII-S model	13.3.4	
	Influence of climate change on groundwater usage and biosphere dose conversion factors	13.3.5, 13.3.7	

a. Adapted from DIRS 155950-BSC (2001, Table 1-1, pp. 1T-1 to 1T-6).
b. S&ER - Science and Engineering Report (DIRS 153849 - DOE 2001, all).
c. SSPA - Supplemental Science and Performance Analysis (DIRS 155950-BSC 2001, all).
d. TSPA -Total System Performance Assessment.
e. The temperature dependent corrosion model was not used for this EIS (see Appendix I, Section I.4); the model used for this EIS yields a more conservative result.
f. HLW = high-level radioactive waste.
g. DOE used revised biosphere dose conversion factors for this EIS to conform to the Environmental Protection Agency standard, 40 CFR Part 197.

Final EIS (see Appendix I, Sections I.2 and I.4). The first column of Table 5-4 lists the major process models and a reference to the appropriate section in the Science and Engineering Report (DIRS 153849-DOE 2001, all). The second column lists the individual model elements analyzed in the unquantified uncertainties report. The third column lists sections of Volume 1 of the Supplemental Science and Performance Analysis report (DIRS 155950-BSC 2001, all) that contain additional details on the analysis. The analyses included sensitivity studies or other analysis methods to determine how significant the uncertainty might be. If warranted and possible, changes were made to the Supplemental Science and Performance Analysis model to better characterize the uncertainties; this is noted in the fourth column.

5.2.4.3.6 *Key Parameters and Uncertainty*

DOE performed an analysis to determine which parameters contributed most to the uncertainties in the long-term performance results for the nominal scenario reported in Section 5.4. Such important parameters will be the greatest contributors to variations in calculated impacts because of the high sensitivity of the results to the parameter or high uncertainty in the parameter. In any case, the range of values in the distribution for these parameters exerts the strongest influence on the uncertainty of the results.

Two types of analysis were used: stepwise linear rank regression and classification tree [in which parameters were classified in terms of the separation of outcomes into “high”-dose (top 10th-percentile) and “low”-dose (bottom 10th-percentile) categories] (DIRS 155934-Mishra 2001, all; DIRS 155936-Mon 2001, all).

Regression Analysis

Regression analysis is a tool for quantifying the strength of input-output relationships in the TSPA model. To this end, a stepwise linear rank regression model is fitted between individual dose at a given time (or some other performance measure) and all randomly sampled input variables. Parameters are ranked on the basis of how much their exclusion would degrade the explanatory power of the regression model. The importance ranking measure used for this purpose is the uncertainty importance factor, which is defined as the loss in explanatory power divided by the coefficient of determination of the regression model. The uncertainty importance factor quantifies the proportion of the total spread (variance) in total dose explained by the regression model that can be attributed to the variable of interest.

Classification Tree Analysis

Classification tree analysis, a subset of classification and regression tree analysis, is a method for determining variables or interactions of variables that drive output into particular categories. Classification and regression tree analyses can be used to generate decision rules that determine whether a particular realization would produce "high" or "low" dose depending on the values of the most important variables. Unlike regression analysis, which is based on the total range of model outcomes, classification tree analysis focuses on extreme values of model results and tries to relate them to specific ranges of values for the important variables.

Results

For different time frames in the analysis, different parameters emerge as important to the overall variability of the results (DIRS 155934-Mishra 2001, all and DIRS 155936-Mon 2001, all). Table 5-5 lists the results of the analysis.

Table 5-5. Top-ranking uncertainty importance parameters.[a]

Time after closure	Two most important parameters
125,000 years	General humid air corrosion rate of Alloy-22 outer lid
	General humid air corrosion rate of Alloy-22 inner lid
250,000 years	General humid air corrosion rate of Alloy-22 outer lid
	General humid air corrosion rate of Alloy-22 inner lid
500,000 years	Episodic factor
	General humid air corrosion rate of Alloy-22 outer lid
1,000,000 years	Episodic factor
	Infiltration scenario

a. Sources: DIRS 155934-Mishra (2001, all) and DIRS 155936-Mon (2001, all).

A description of the important parameters identified in Table 5-5 follows:

- *General Humid Air Corrosion Rates of Alloy-22, Inner and Outer Lids* – When the drip shields are intact and no water is dripping on the waste package, the corrosion rate of Alloy-22 is governed by the humid air corrosion rates of the inner lid and the outer lid. The waste package closure end has three lids: an innermost stainless-steel lid, an inner Alloy-22 lid, and an outer Alloy-22 lid. These two corrosion rate parameters govern how the respective Alloy-22 lids degrade when not exposed to dripping water.

- *Episodic Factor* – The conceptual model governing episodic infiltration represents fractures comprised of randomly distributed "pinch-point" and "storage" apertures. Pinch-point apertures act as capillary barriers to the infiltration of water, which accumulates in a volume above the pinch-point dictated by the storage aperture. The water continues to accumulate in the storage aperture until the hydraulic head above the pinch-point aperture exceeds the associated capillary rise height. Once this threshold is reached, the water begins to flow downward under the force of gravity at a rate dictated by the permeability of the aperture. Water continues to flow through the aperture until the accumulated water is completely drained. This behavior leads to an episodic infiltration of water through fractured rock that occurs randomly in space and time. The distribution of a factor that is randomly sampled governs this episodic flow in the numerical model.

- *Infiltration Scenario* – For each of the six *climate states* (see Appendix I, Section I.2.2) there are three possible infiltration rates (low, medium, and high). The particular climate state and infiltration rate is the infiltration scenario. Therefore, this variable is a function of the infiltration rate.

The parameters in Table 5-5 that most affect the total uncertainty in the TSPA model are factors that would govern the degradation of the waste package for the first 250,000 years following repository closure. After 250,000 years, most waste packages would have failed and other factors become important. Even at 500,000 years after repository closure, waste package degradation is still important. At later times the important parameters would be related to factors that influenced the flow of water in the drifts, especially infiltration and episodic flow.

5.3 Locations for Impact Estimates

Yucca Mountain is in the transition area between the Mojave Desert and the Great Basin. This is a semiarid region with linear mountain ranges and intervening valleys, with rainfall averaging between about 100 and 250 millimeters (4 and 10 inches) a year, sparse vegetation, and a small population. Although there is low infiltration of water through the mountain and no people currently live in the land withdrawal area, radioactive and chemically toxic materials released from the repository could affect persons living closer to the proposed repository in the distant future. This section describes the regions where possible human health impacts could occur.

Figure 5-3 is a map with arrows showing the general direction of groundwater movement from Yucca Mountain. Shading indicates major areas of groundwater discharge through a combination of springs and evapotranspiration by plants. The general path of water that infiltrates through Yucca Mountain is south toward Amargosa Valley, into and through the area around Death Valley Junction in the lower Amargosa Desert. Natural discharge of groundwater from beneath Yucca Mountain probably occurs farther south at Franklin Lake Playa (DIRS 100376-Czarnecki 1990, pp. 1 to 12), and spring discharge in Death Valley is a possibility (DIRS 100131-D'Agnese et al. 1997, pp. 64 and 69).

Although groundwater from the Yucca Mountain vicinity flows under and to the west of Ash Meadows in the volcanic tuff or alluvial aquifers, the surface discharge areas at Ash Meadows and Devils Hole (see map in Figure 5-3 for locations) are fed from the carbonate aquifer. While these two aquifers are connected at some locations, the carbonate aquifer has a hydraulic head that is higher than that of the volcanic or alluvial aquifers. Because of this pressure difference, water from the volcanic aquifer does not flow into the carbonate aquifer; rather, the reverse occurs. Therefore, contamination from Yucca Mountain is not likely to mix with the carbonate waters and discharge to the surface at Ash Meadows or Devils Hole (DIRS 104983-CRWMS M&O 1999, all) under current conditions. This pressure difference could change under future climate conditions.

Because, under expected conditions, there would be no contamination of this discharge water, there would be no human health impacts. Furthermore, there would be no consequences to the endangered Ash Meadows Amargosa pupfish (*Cyprinodon nevadensis mionectes*) or Devils Hole pupfish (*Cyprinodon diabolis*) at those locations.

Figure 3-25 in Chapter 3 shows the projected population of 76,000 residents within 80 kilometers (50 miles) of Yucca Mountain in 2035. This map provides the information used to estimate population doses from radionuclides released to the atmosphere from the repository. The atmospheric analysis in Section 5.5 used the 80-kilometer (50-mile) population distribution described in Section 3.1.8.

In the Draft EIS, impacts were evaluated at 5-kilometer (3-mile), 20-kilometer (12-mile), and 30-kilometer (19-mile) distances from the repository as well as at the groundwater discharge point. The EPA regulation, 40 CFR 197.12, establishes a controlled area around the repository that must not extend farther south than 36 degrees, 40 minutes, 13.6661 north latitude, in the predominant direction of groundwater flow. For this EIS, DOE assumed the controlled area boundary to be the farthest point south. The predominant groundwater flow crosses this boundary approximately 18 kilometers (11 miles) from the repository. Therefore, the 5-kilometer (3-mile) distance would be inside the controlled area, would no longer be part of the accessible environment, and DOE did not evaluate impacts at this distance.